Data & Client Oriented Consistency, Protocols, Replication

7 June 2026
Lecture 12

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Topics for Today

- Data Oriented Consistency
- Client centric consistency
- Consistency Protocols
- Replica management
  - Content Replication
  - Content Distribution

Sources:

- TvS 7.1-7.5, 8

Performance and Scalability

Main issue: To keep replicas consistent, we generally need to ensure that all **conflicting** operations are done in the same order everywhere

Conflicting operations: From the world of transactions:

- **Read-write conflict**: a read operation and a write operation act concurrently
- **Write-write conflict**: two concurrent write operations

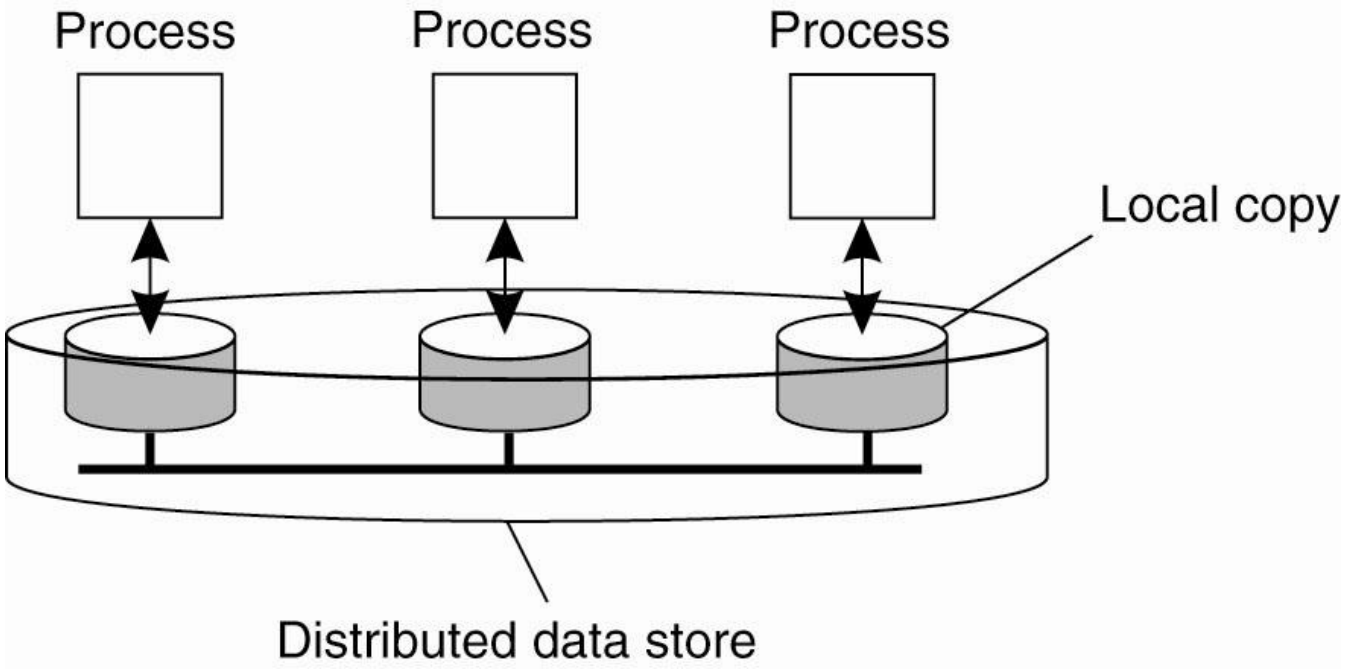
Guaranteeing global ordering on conflicting operations may be a costly operation, downgrading scalability

Solution: weaken consistency requirements so that hopefully global synchronization can be avoided

Data-Centric Consistency Models

Consistency model: a contract between a (distributed) data store and processes, in which the data store specifies precisely what the results of read and write operations are in the presence of concurrency.

Essence: A data store is a distributed collection of storages accessible to clients:



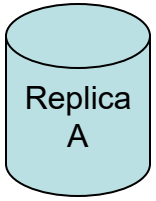
Continuous Consistency

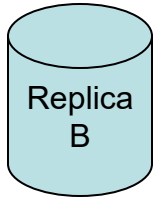
Observation: We can actually talk a about a **degree of consistency**:

- replicas may differ in their **numerical value**
  - Value **may be how many updates are missing**
  - Weight **may be the mathematical distance**
- replicas may differ in their relative **staleness**
- there may be differences with respect to (number and order) of **performed update operations**

Conit: consistency unit → specifies the **data unit** over which consistency is to be measured.

Example: Conit Dimensions





VC [A,B]	Committed		Tentative		Event
	x	y	x	y	
[0,0]	0	0	0	0	Init
[0,5]	0	0	2	0	Receive [0,5] from B
[1,5]	2	0	2	0	Commit [0,5]
[8,5]	2	0	2	2	y := y +2
[12,5]	2	0	2	3	y := y + 1
[14,5]	2	0	6	3	x := y * 2

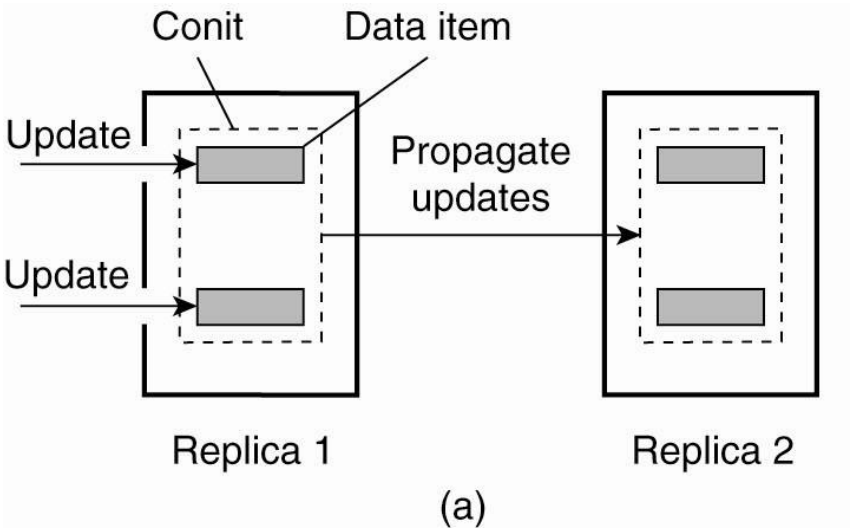
VC [A,B]	Committed		Tentative		Event
	x	y	x	y	
[0,0]	0	0	0	0	Init
[0,5]	0	0	2	0	x := x+2
[0,6]	0	0	2	0	Send [0,5] to A
[0,10]	0	0	2	5	y := y + 5

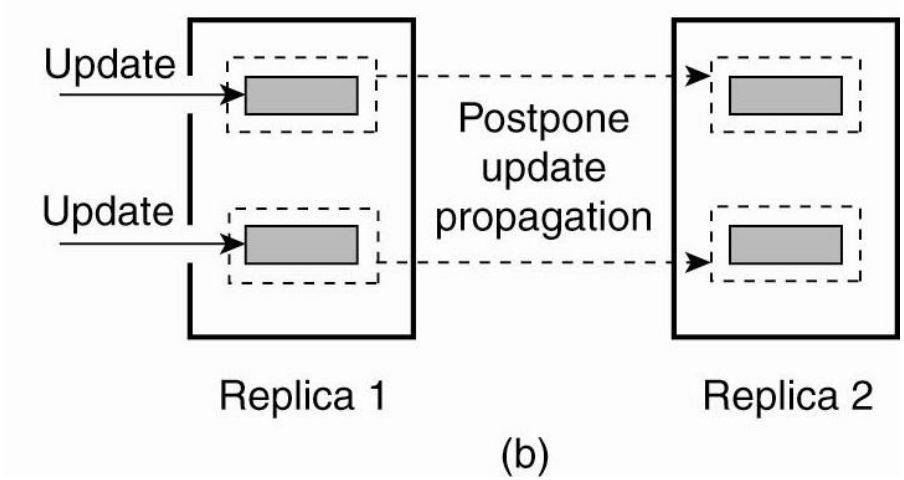
- Dimension 1: **Updates received, not committed**: A = 3, B = 2
- Dimension 2: **Updates a replica didn't see**: A = 1, B = 3
- Dimension 3: **Numerical deviation from missing updates**:
  - A = 5 (x missing 0, y missing 5), B = 6 (x missing 6, y missing 3)

Conits

- The granularity of your conit is important
- With a given consistency policy:
  - Smaller conits mean you may defer pushing updates
  - Bigger conits mans you must push earlier

Example: Do you update a whole table? Each row in the table? Each entry/cell in the row?

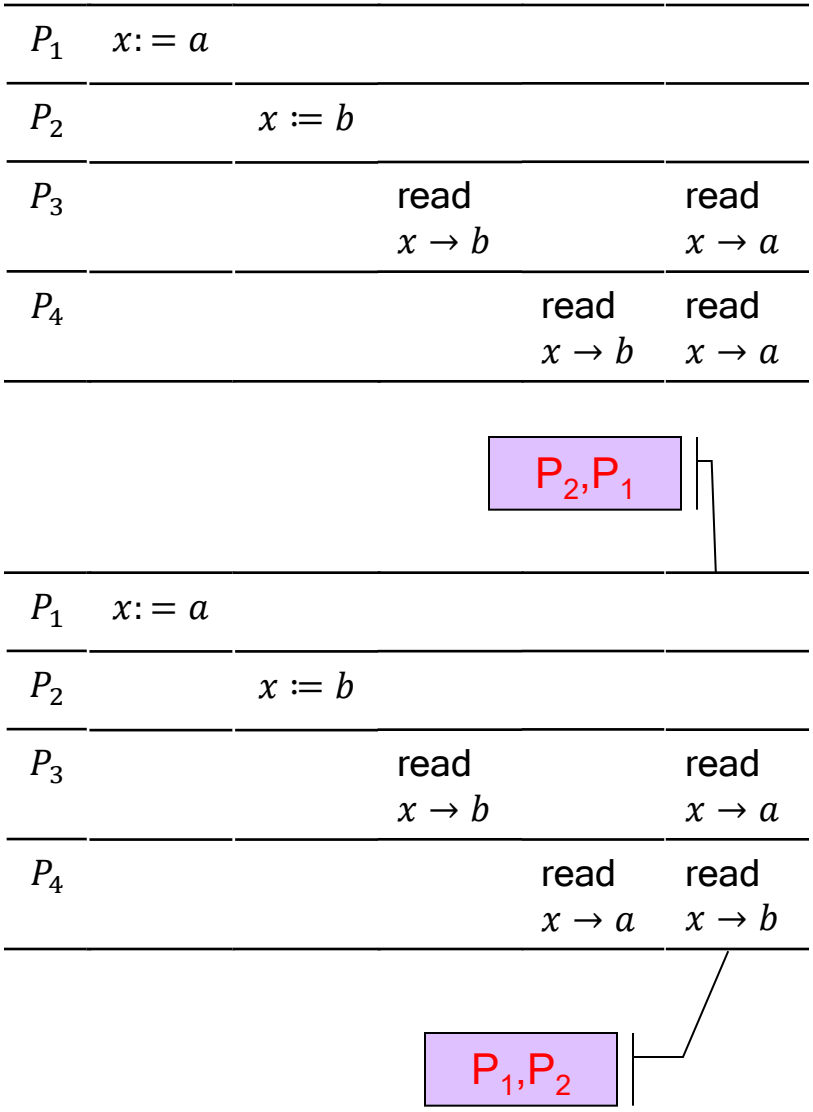




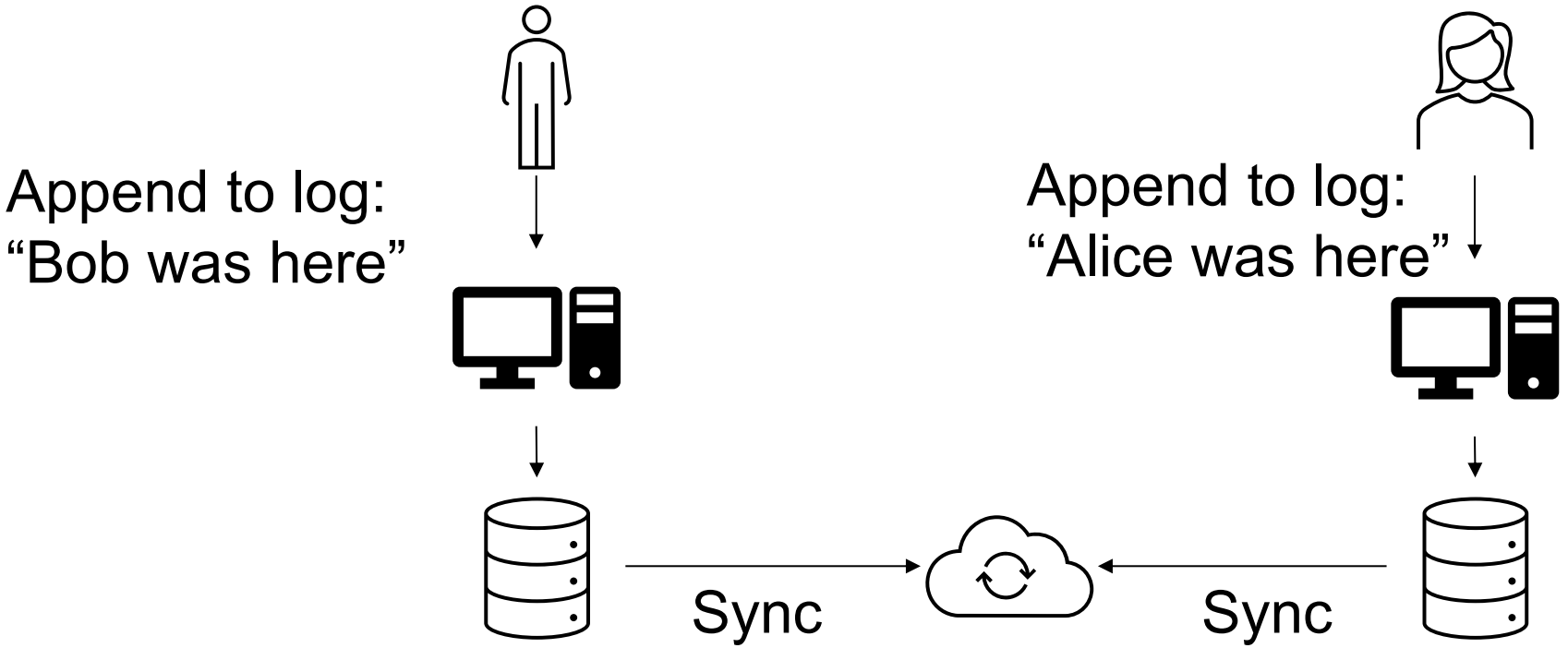
Sequential Consistency

The result of any execution is the same as if the operations of all processes were executed in some sequential order, and the operations of each individual process appear in this sequence in the order specified by its program.

Note: We're talking about **interleaved** executions: there is some total ordering for all operations taken together.



Sequential Consistency



Potential log contents:

Alice was here Bob was here	Bob was here Alice was here

Both see the same outcome on their local copies

Causal Consistency

Writes that are potentially causally related must be seen by all processes in the same order. Concurrent writes may be seen in a different order by different processes.

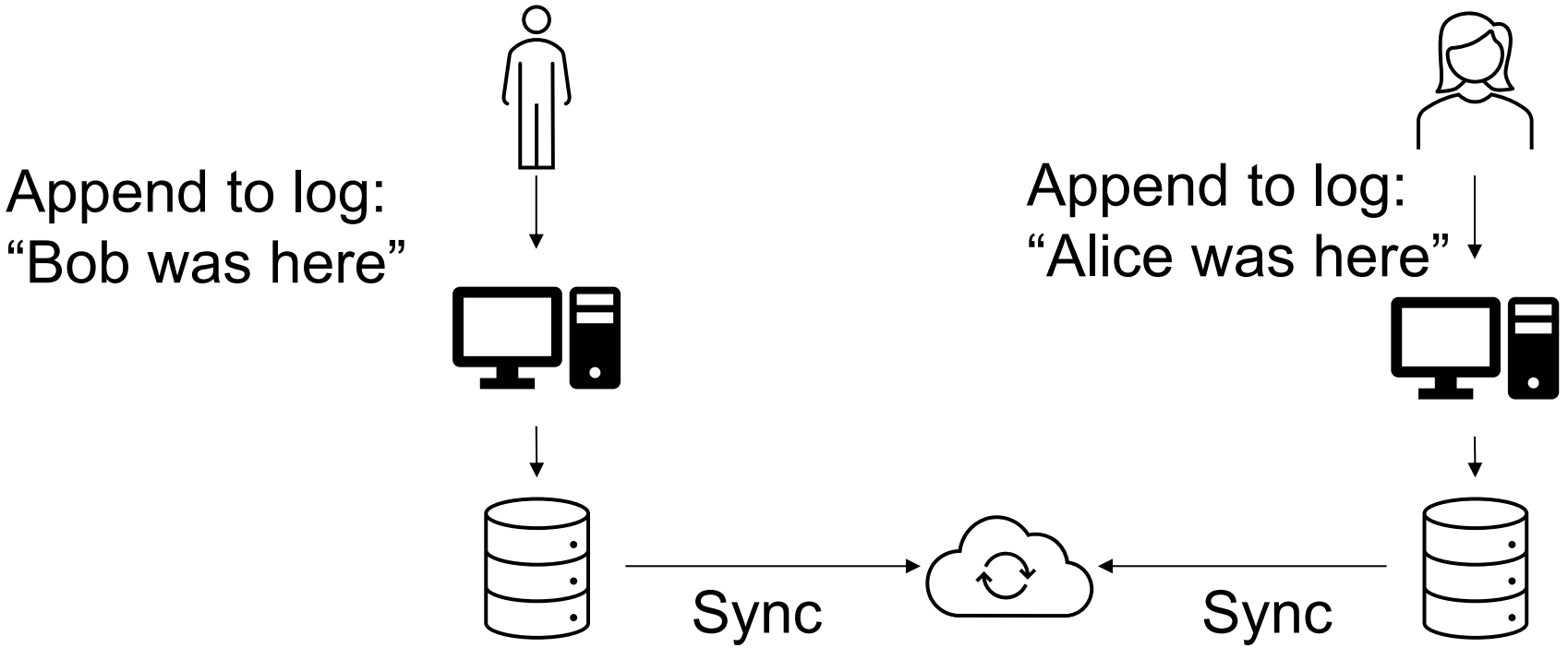
P_1	$x := a$		$x := c$	
P_2		read $x \to a$	$x := b$	
P_3		read $x \to a$	read $x \to c$	read $x \to b$
P_4		read $x \to a$	read $x \to b$	read $x \to c$

OK

P_1	$x := a$			
P_2		read $x \to a$	$x := b$	
P_3			read $x \to b$	read $x \to a$
P_4			read $x \to a$	read $x \to b$

P_1	$x := a$			
P_2		$x := b$		
P_3			read $x \to b$	read $x \to a$
P_4			read $x \to a$	read $x \to b$

Causal Consistency



Potential log contents:

Alice was here Bob was here	Bob was here Alice was here

They might see different versions on their local copies

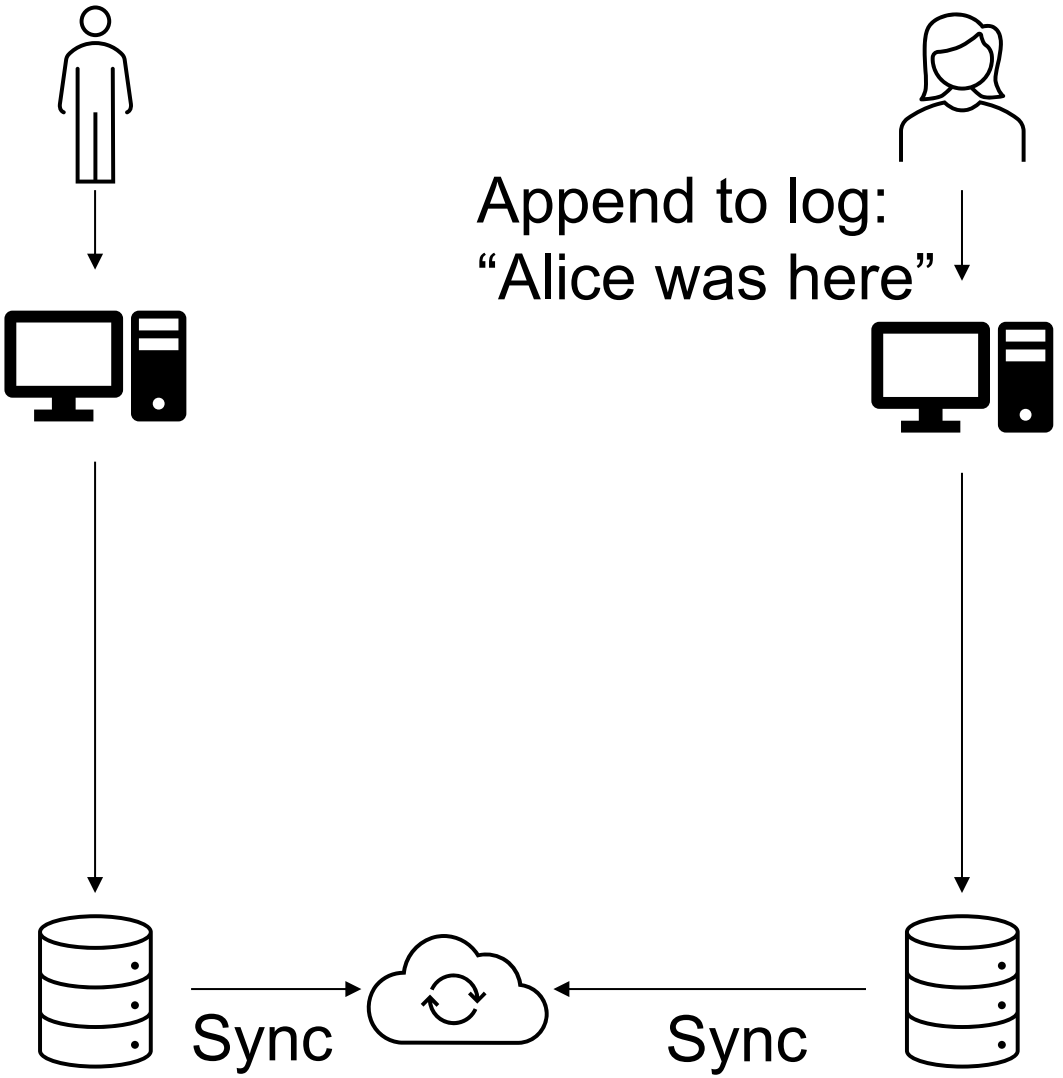
Causal Consistency

1. Read Log and sees “Alice was here”

Then

2. Append to log: “Bob was here”

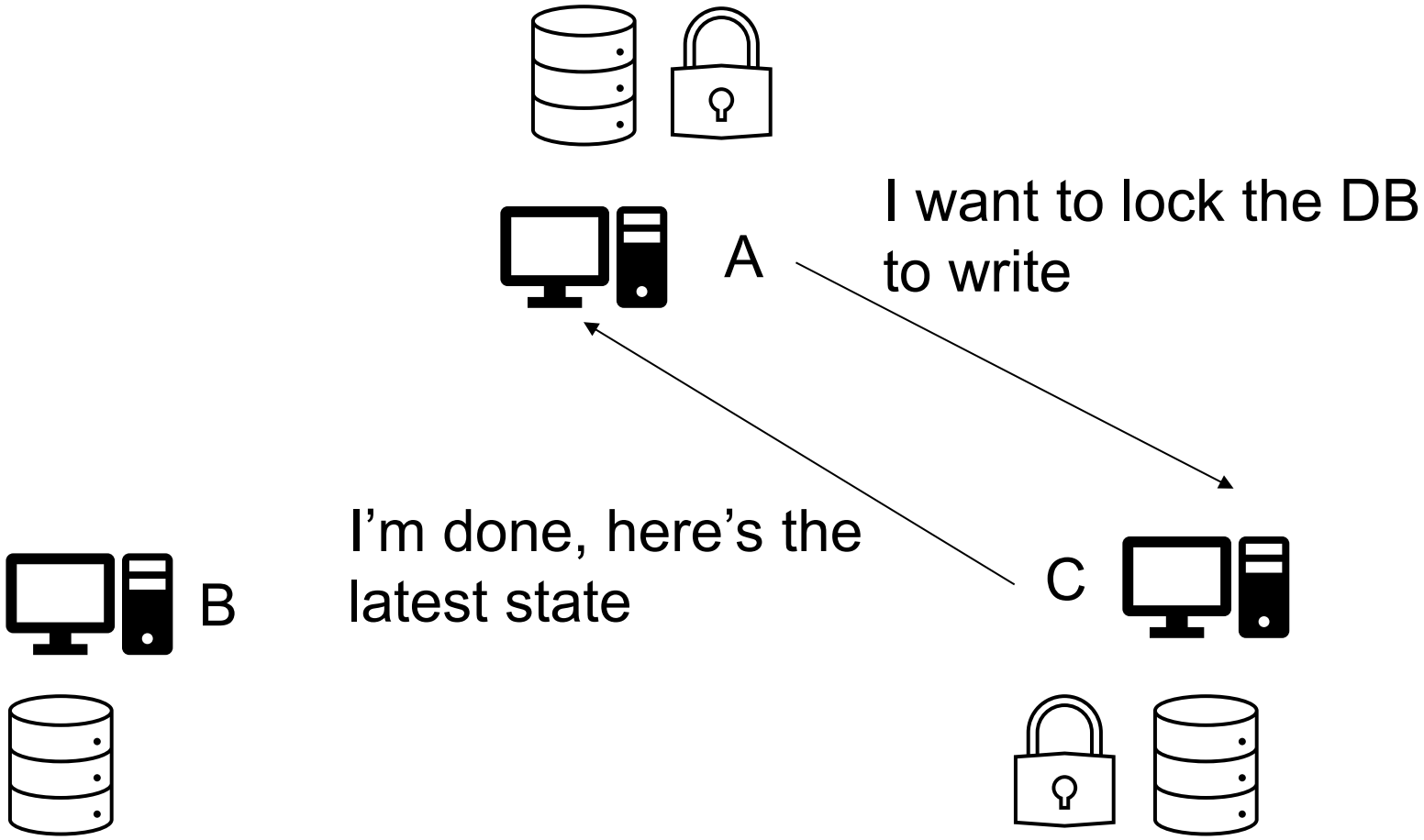
Append to log: “Alice was here”



Potential log contents:

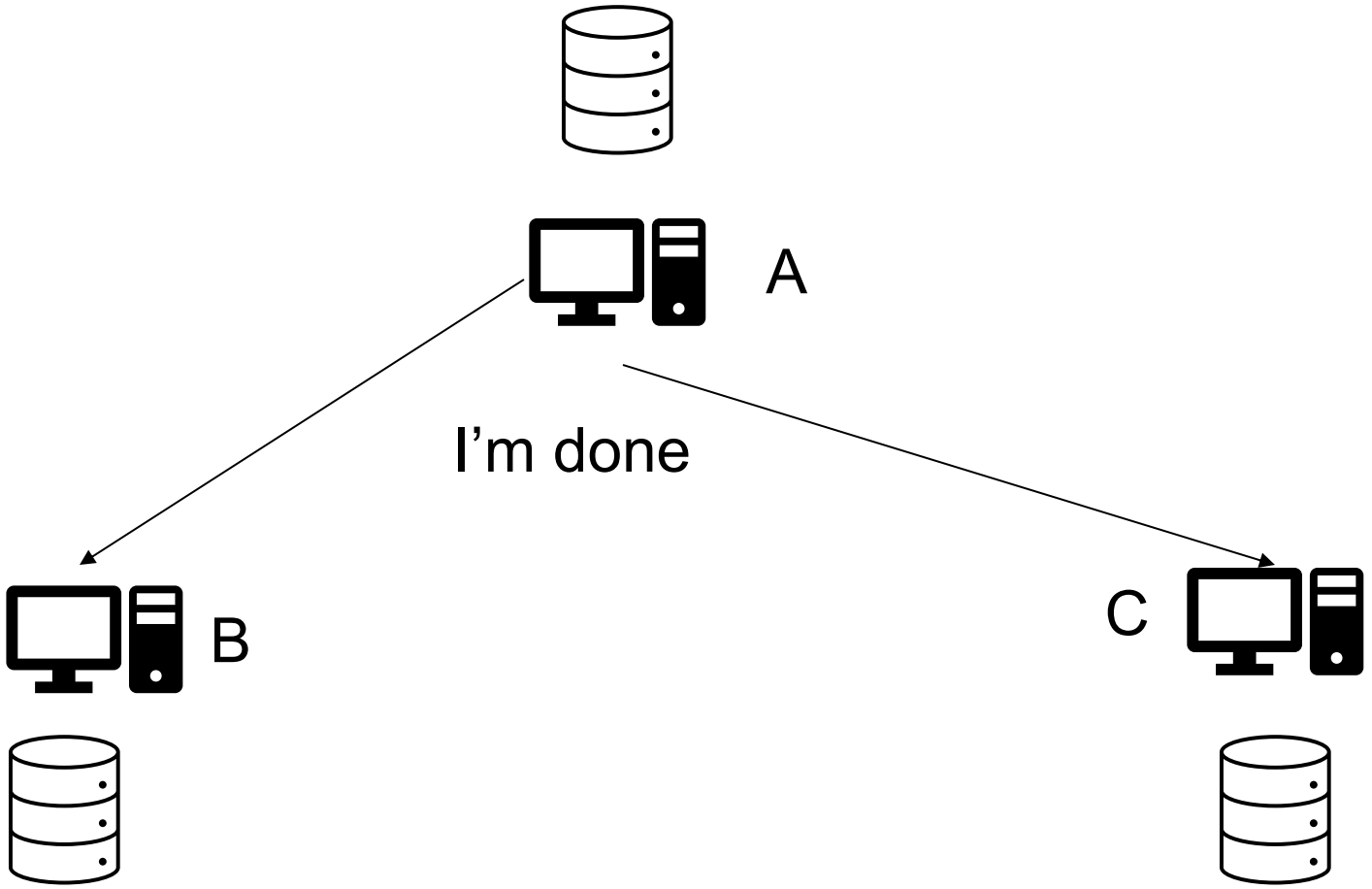
Alice was here
Bob was here

Grouping Operations

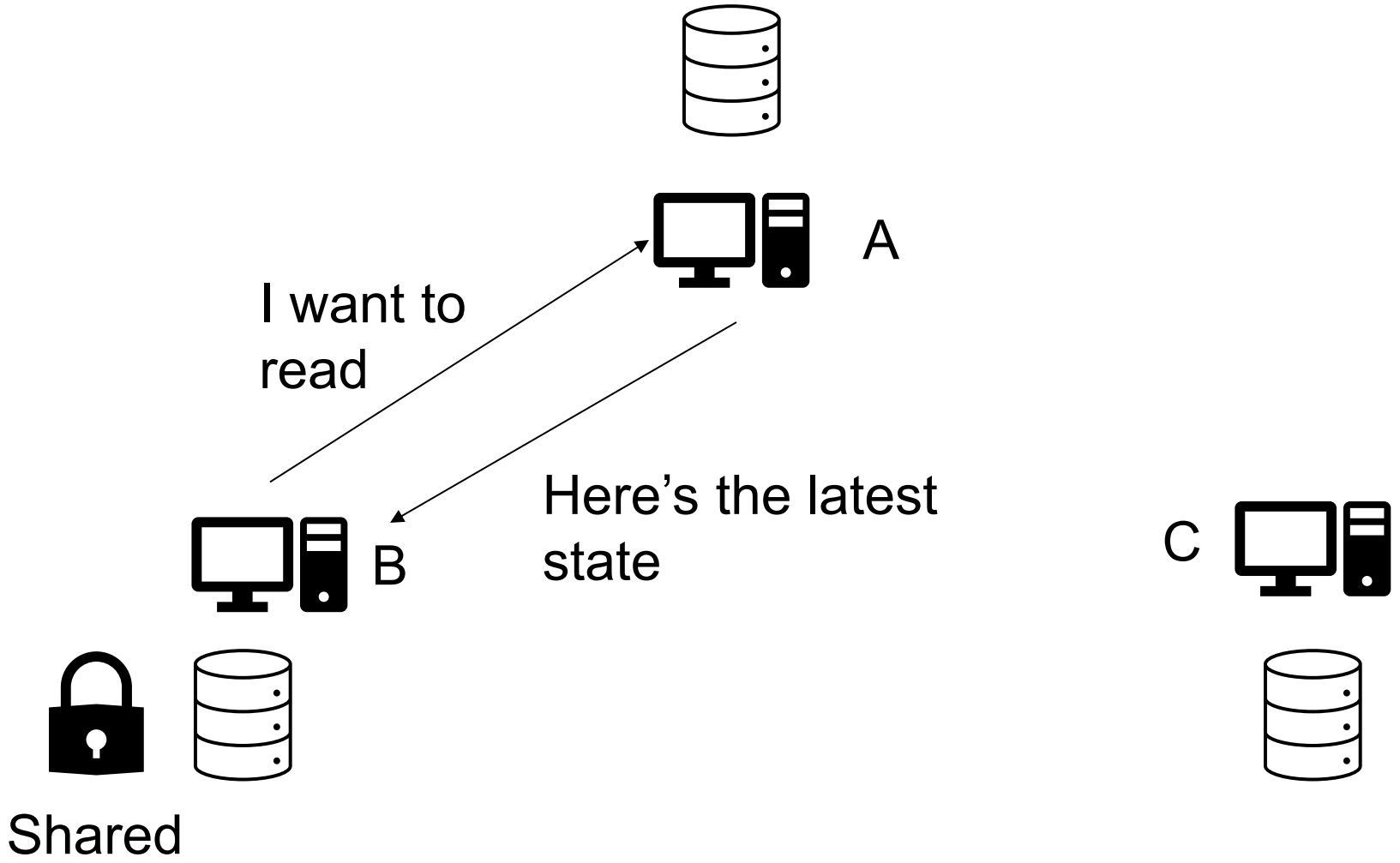


Grouping Operations

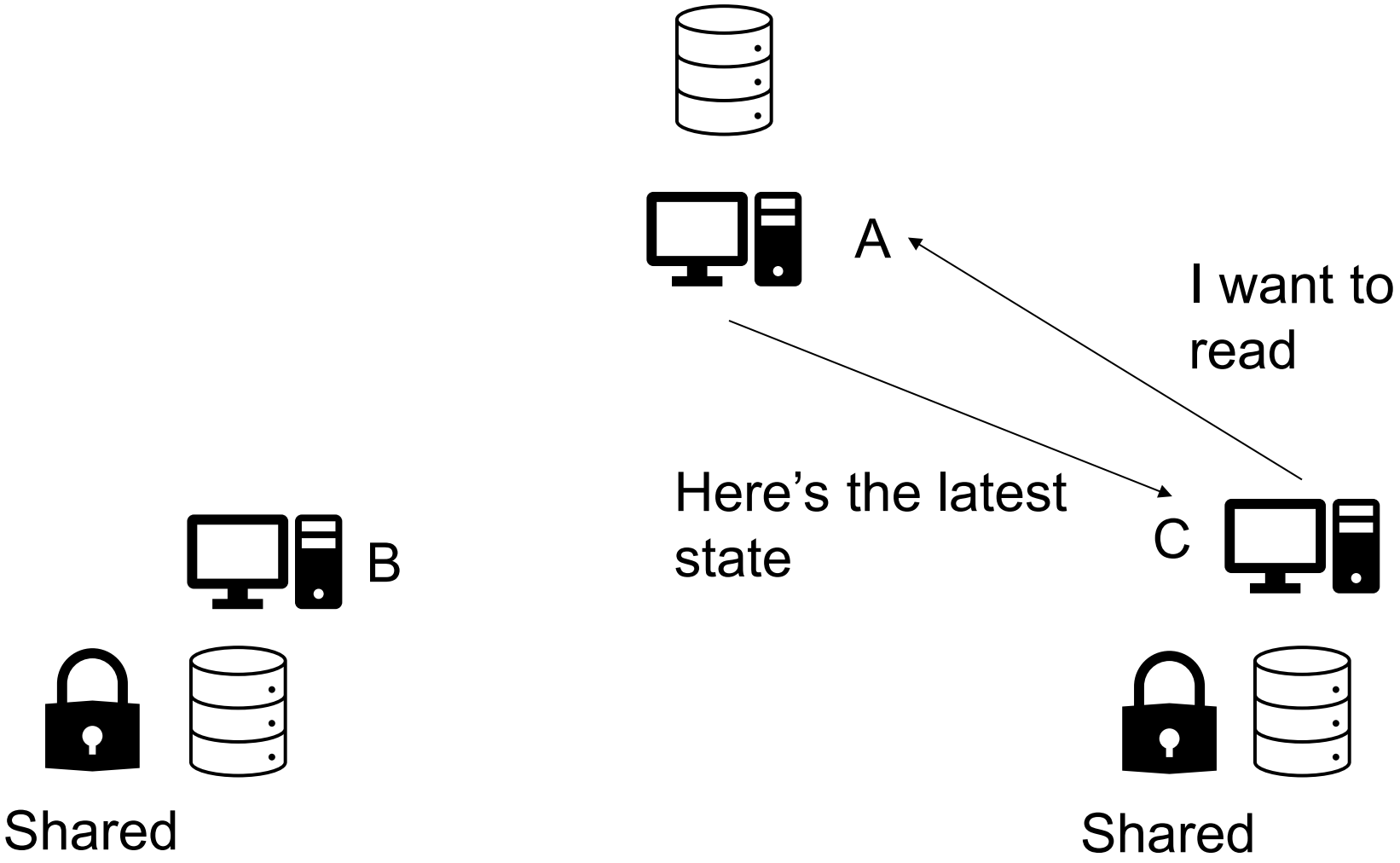
Grouping Operations



Grouping Operations



Grouping Operations



Grouping Operations

Exclusive Lock 

- Get the state from the last lock owner
- Lock the resource exclusively

Non-Exclusive Lock 

- Get a copy of the state from the current/former lock owner
- Lock the resource shared

Basic idea:
You don't care if reads and writes of a series of operations are immediately known or known later.

Want the effect of the series itself to be known.

Grouping Operations

P_1	$Acq(Lock(x))$	$x := a$	$Acq(Lock(y))$	$y := b$	$Rel(Lock(x))$	$Rel(Lock(y))$		
P_2						$Acq(Lock(x))$	read $x \to a$	read $y \to n$
P_3							$Acq(Lock(y))$	read $y \to b$

Observation: Weak consistency implies that we need to lock and unlock data (implicitly or not).

Question: What would be a convenient way of making this consistency more or less transparent to programmers?

So Far

- Data Oriented Consistency
- Client centric consistency
- Consistency Protocols
- Replica management
  - Content Replication
  - Content Distribution

Client-centric Consistency Models

Overview:

- System Model
- Monotonic reads
- Monotonic writes
- Read-your-writes
- Write-follows-reads

Goal

Show how we can perhaps avoid system-wide consistency, by concentrating on what specific clients want, instead of what should be maintained by servers.

Consistency for Mobile Users

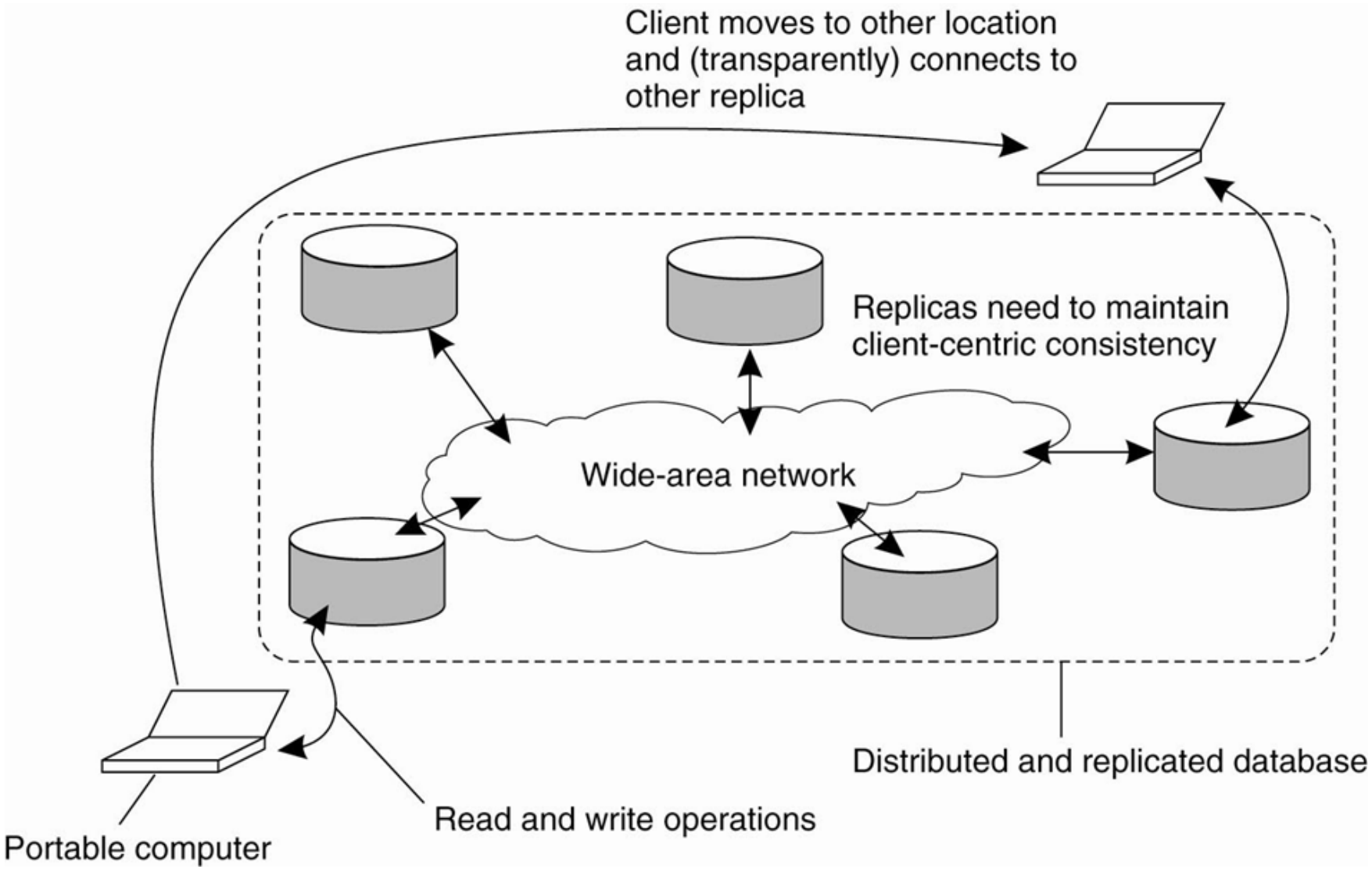
Example: Consider a distributed database to which you have access through your notebook. Assume your notebook acts as a front end to the database.

- At location A you access the database doing reads and updates.

- At location B you continue your work, but unless you access the same server as the one at location A, you may detect inconsistencies:
  - your updates at A may not have yet been propagated to B
  - you may be reading newer entries than the ones available at A
  - your updates at B may eventually conflict with those at A

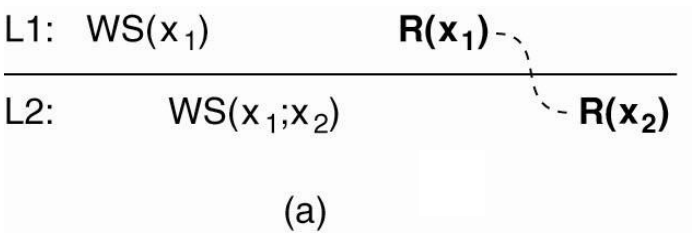
Note: The only thing you really want is that the entries you updated and/or read at A, are in B the way you left them in A. In that case, the database will appear to be consistent to you.

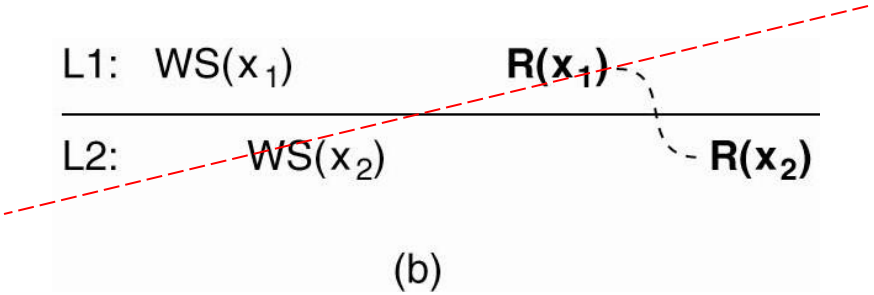
Basic Architecture



Monotonic Reads (1/2)

If a process reads the value of a data item x, any successive read operation on x by that process will always return that same or a more recent value.

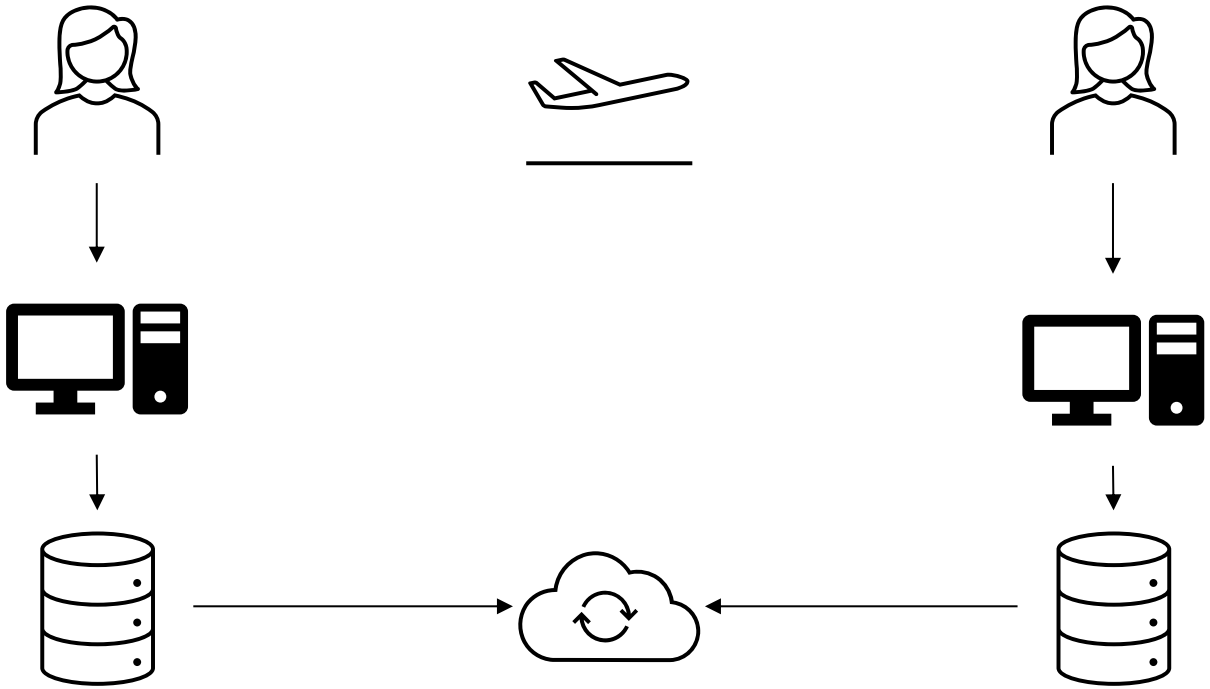




Notation: $WS(x_i[t])$ is the set of write operations (at L_i) that lead to version x_i of x (at time t); $WS(x_i[t_1]; x_j[t_2])$ indicates that it is known that $WS(x_i[t_1])$ is part of $WS(x_j[t_2])$.

Note: Parameter t is omitted from figures

Monotonic Reads



File1 last modified at 10:11am
File2 last modified at 9:14am
File3 last modified at 6:45pm

File1 last modified at 10:51am
File2 last modified at 9:14am
File3 last modified at 7:50pm

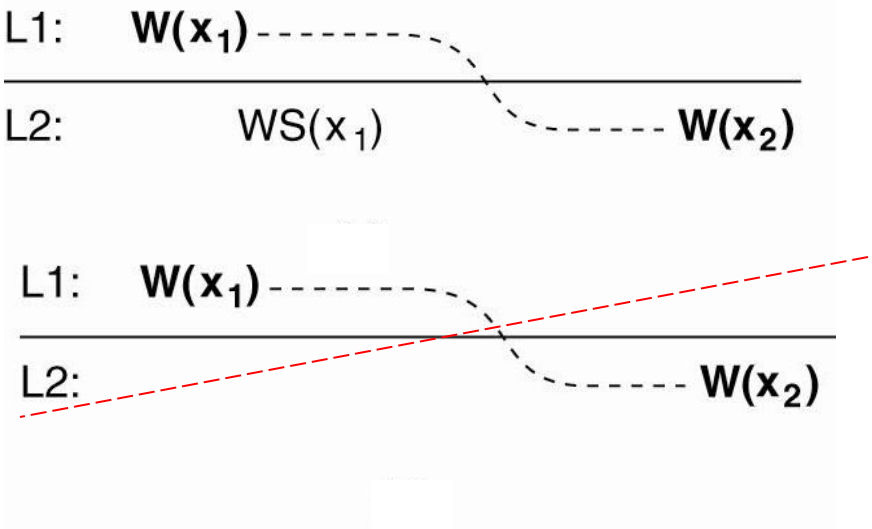
Monotonic Reads (2/2)

Example: Automatically reading your personal calendar updates from different servers. Monotonic Reads guarantees that the user sees all updates, no matter from which server the automatic reading takes place.

Example: Reading (not modifying) incoming mail while you are on the move. Each time you connect to a different e-mail server, that server fetches (at least) all the updates from the server you previously visited.

Monotonic Writes

A write operation by a process on a data item x is completed before any successive write operation on x by the same process.

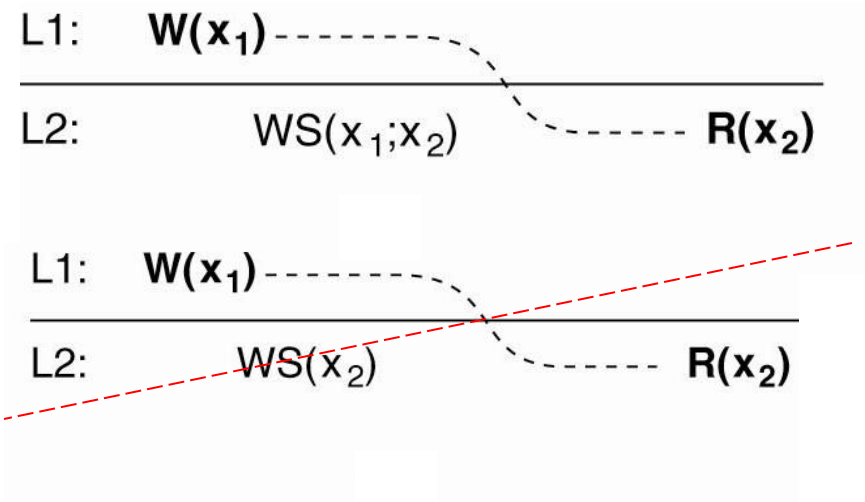


Example: Updating a program at server $S2$, and ensuring that all components on which compilation and linking depends, are also placed at $S2$.

Example: Maintaining versions of replicated files in the correct order everywhere (propagate the previous version to the server where the newest version is installed).

Read Your Writes

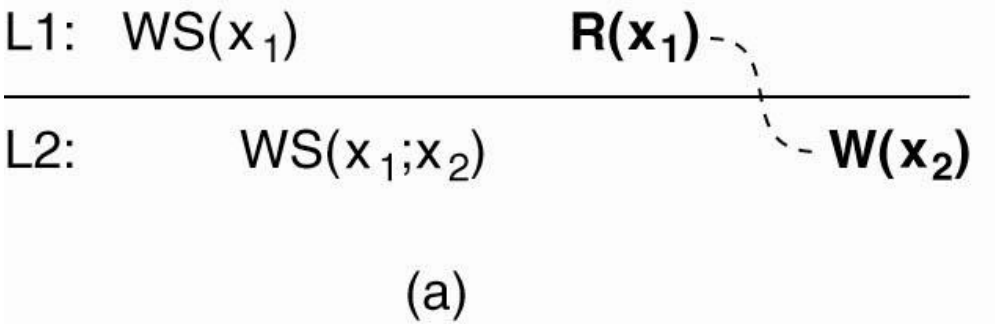
The effect of a write operation by a process on data item x, will always be seen by a successive read operation on x by the same process.

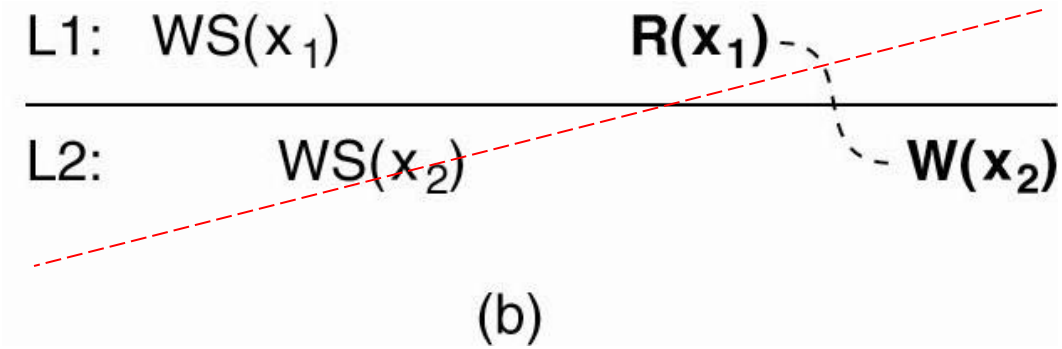


Example: Updating your Web page and guaranteeing that your Web browser shows the newest version instead of its cached copy.

Writes Follow Reads

A write operation by a process on a data item x following a previous read operation on x by the same process, is guaranteed to take place on the same or a more recent value of x that was read.





Example: See reactions to posted articles only if you have the original posting (a read "pulls in" the corresponding write operation).

So Far

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- Consistency Protocols
- Replica management
  - Content Replication
  - Content Distribution

Consistency Protocols

Consistency protocol: describes the implementation of a specific consistency model.

- Continuous consistency
- Primary-based protocols
- Replicated-write protocols

Continuous Consistency: Numerical Errors

Principle: consider a data item x and let $weight(W)$ denote the numerical change in its value after a write operation W. Assume that $\forall W: weight(W) > 0$

W is initially forwarded to one of the N replicas, denoted as $origin(W)$. $TW[i,j]$ are the writes execute by server S_i that originated from S_j:

$$TW[i,j] = \sum\{weight(W) \mid (origin(W) = S_j) \wedge (W \in L_i)\}$$

Note: Actual value $v(t)$ of x:

$$v(t) = v_{init} + \sum_{k=1}^{N} TW[k,k]$$

Value v_i of x at replica i:

$$v_i = v_{init} + \sum_{k=1}^{N} TW[i,k]$$

Continuous Consistency: Numerical Errors

Problem: We need to ensure that $v(t) - v_i < \delta_i$ for every server S_i.

Approach: Let every server S_k maintain a **view** $TW_k[i,j]$ of what it believes is the value of $TW[i,j]$. This information can be gossiped when an update is propagated.

Note: $0 \leq TW_k[i,j] \leq TW[i,j] \leq TW[j,j]$

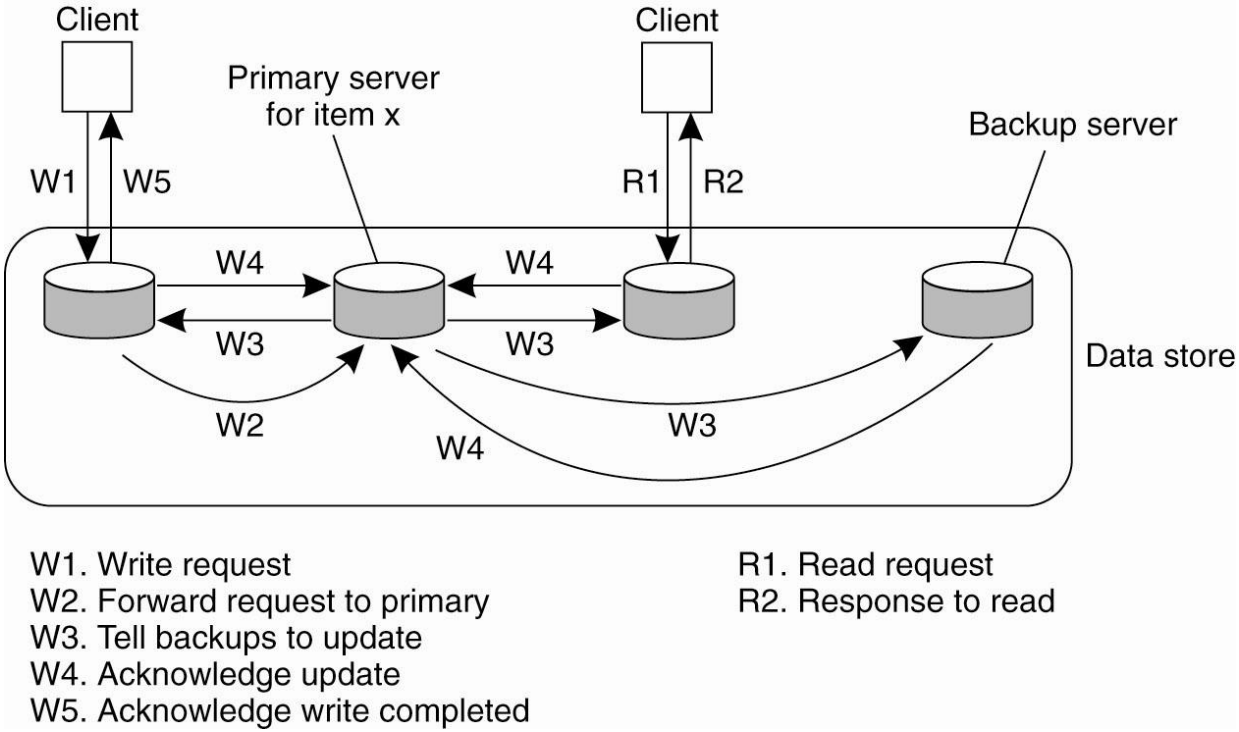
Solution: S_k sends operations from its log to S_i when it sees that $TW_k[i,k]$ is getting too far from $TW[k,k]$, in particular, when

$$TW[k,k] - TW_k[i,k] > \frac{\delta_i}{N-1}$$

Note: Staleness can be done analogously, by essentially keeping track of what has been seen last from S_i (see book).

Primary-Based Protocols (1/2)

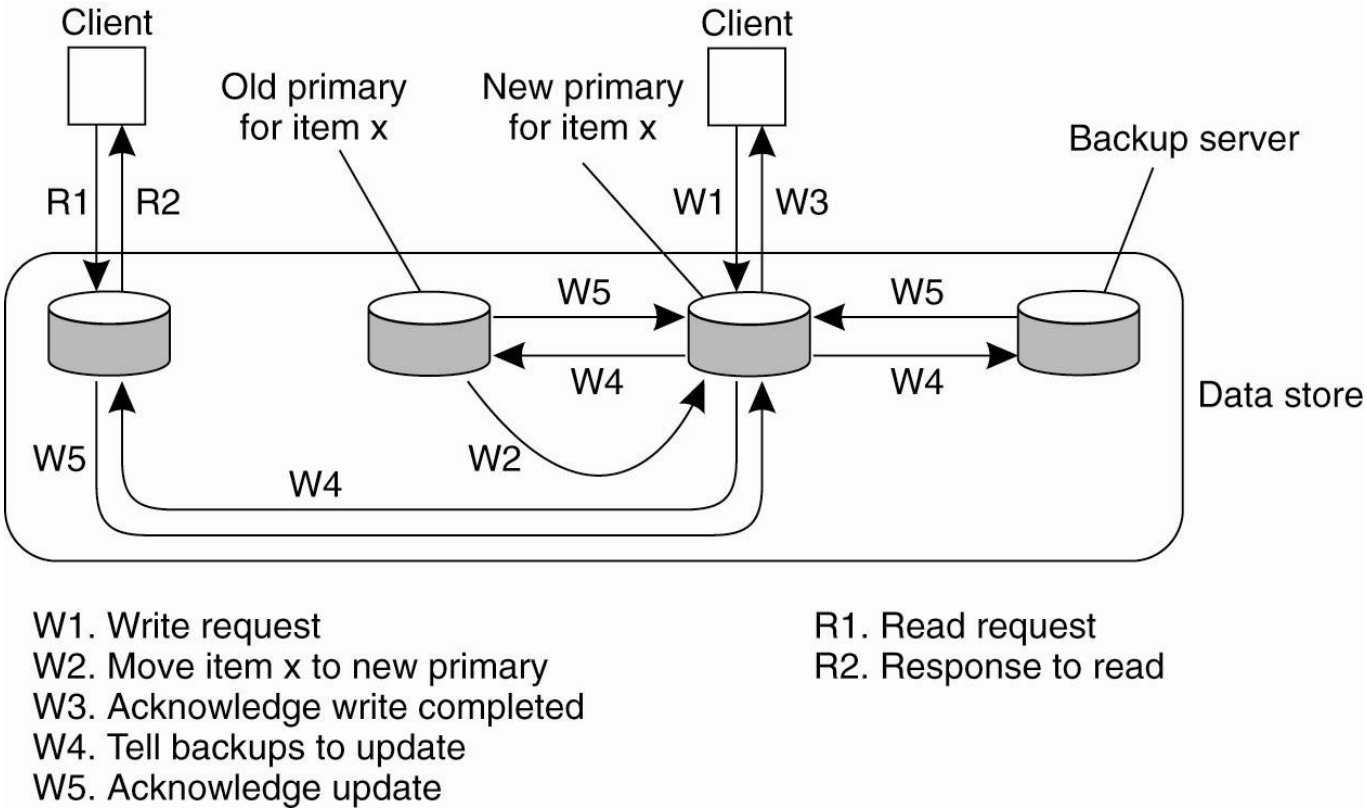
Primary-backup protocol:



Example: Traditionally applied in distributed databases and file systems that require a high degree of fault tolerance. Replicas are often placed on same LAN.

Primary-Based Protocols (2/2)

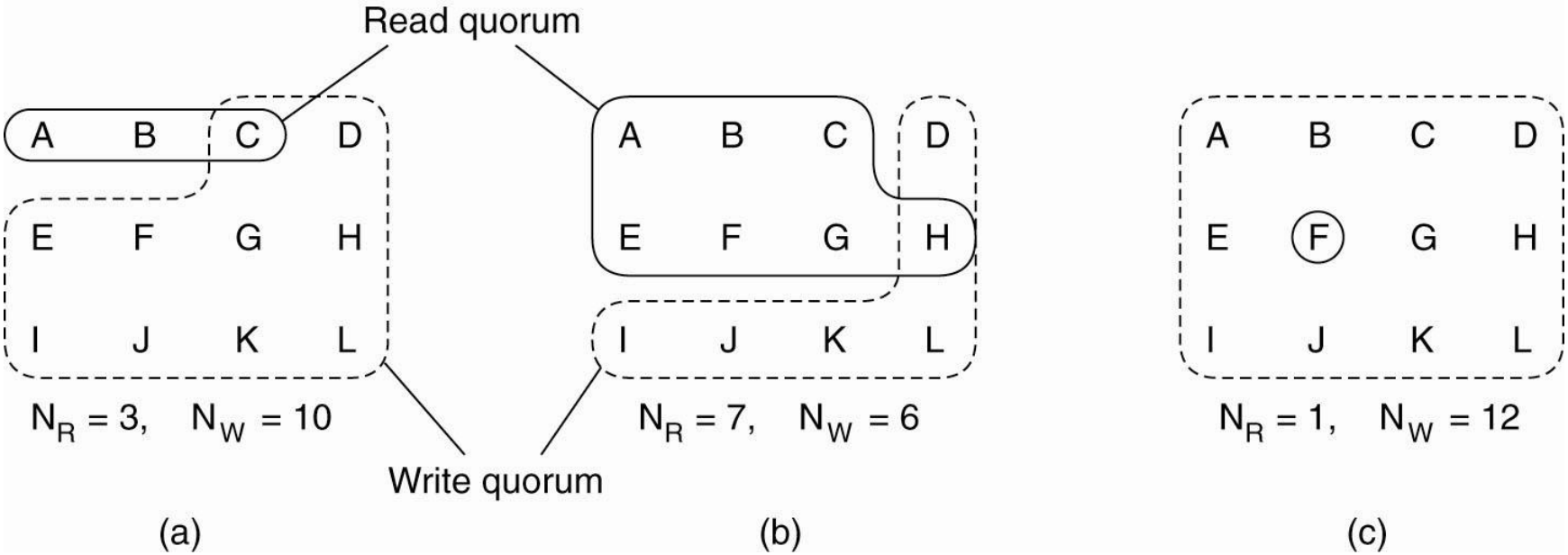
Primary-backup protocol with local writes:



Example: Mobile computing in disconnected mode (ship all relevant files to user before disconnecting and update later).

Replicated-Write Protocols

Quorum-based protocols: Ensure that each operation is carried out in such a way that a majority vote is established: distinguish **read quorum** and **write quorum**:



Replicated Write Issues

Prevents issues with two writes

Still can end up with “split-brain” without protocol to coordinate servers

The larger the write quorum, the less often sync is needed

So Far

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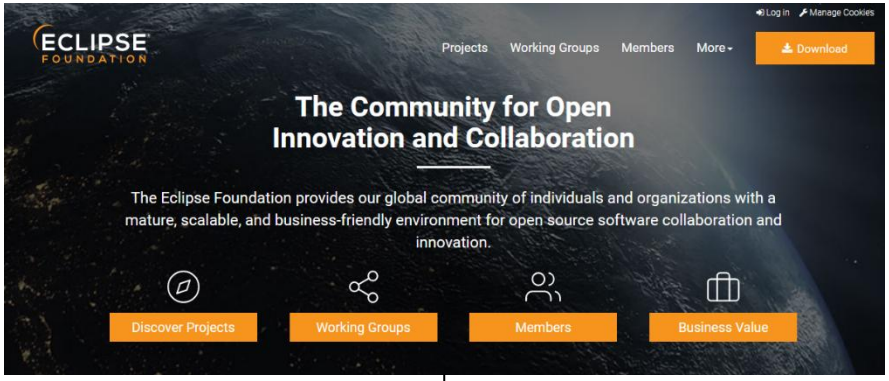
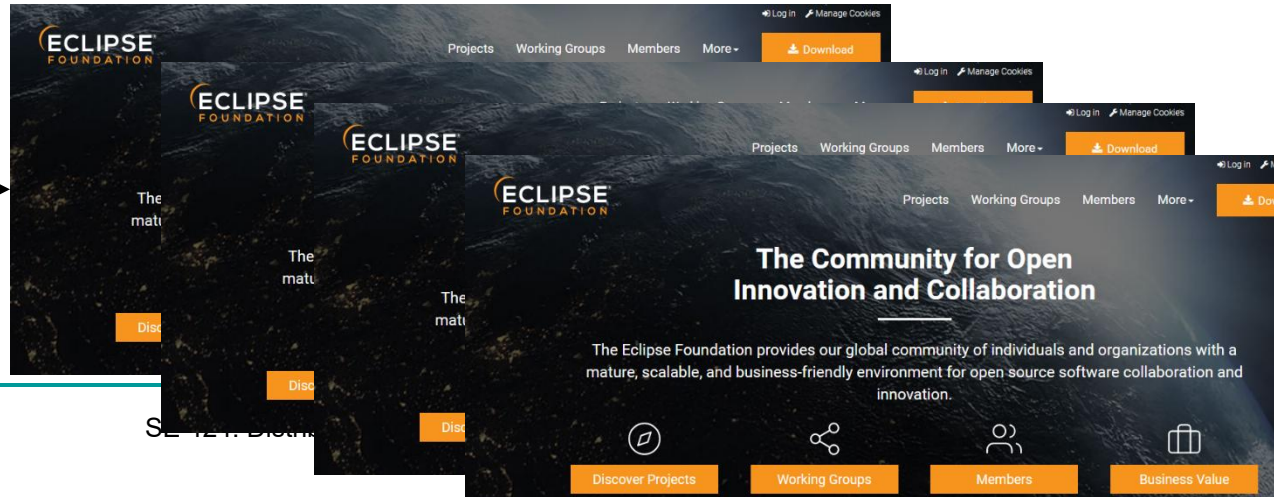
  - Content Distribution

Distribution Protocols

- Replica server placement
- Content replication and placement
- Content distribution

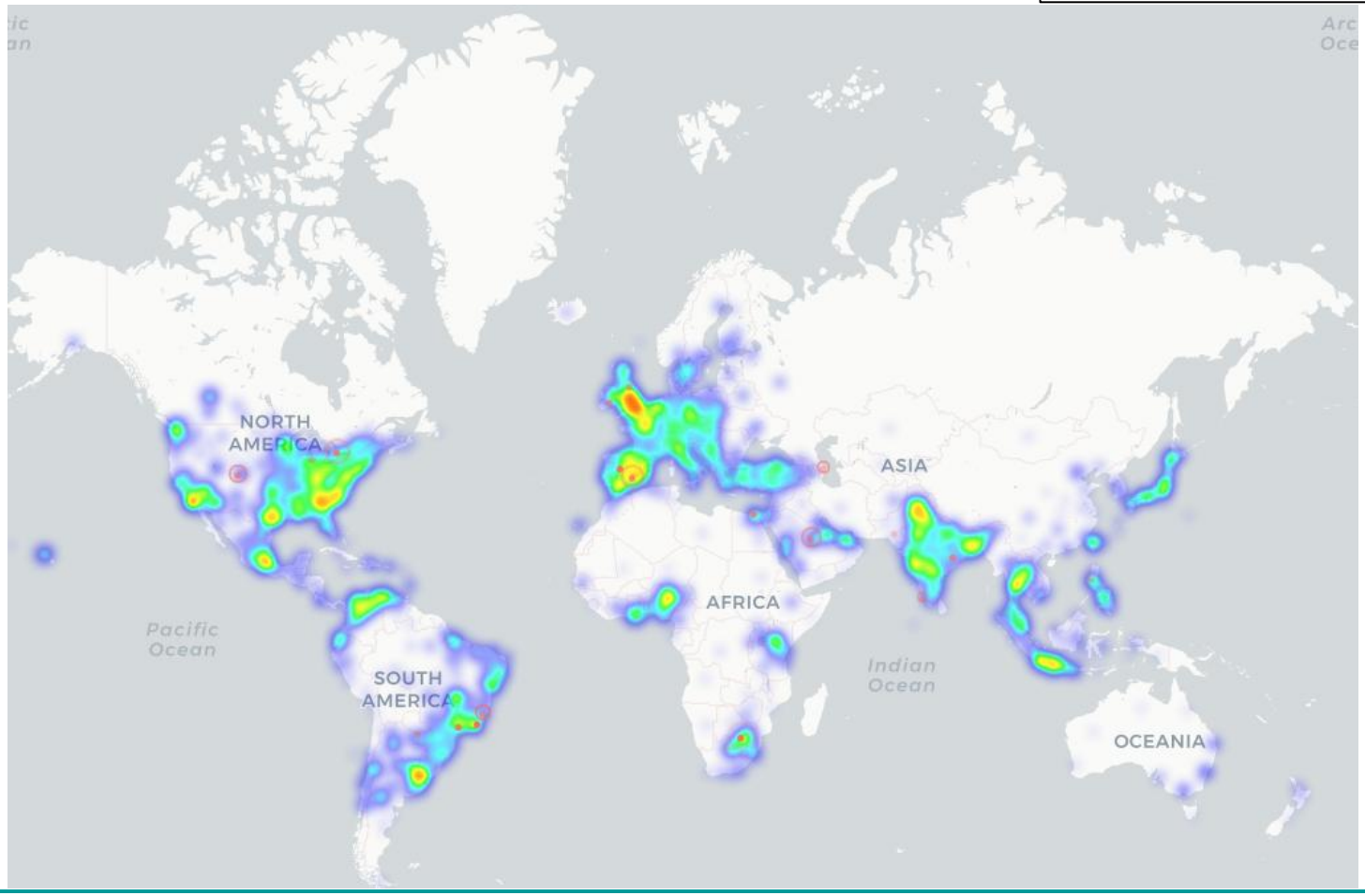




Replica Placement

Essence: Figure out what the best K places are out of N possible locations.

Source: https://onemilliontweetmap.com

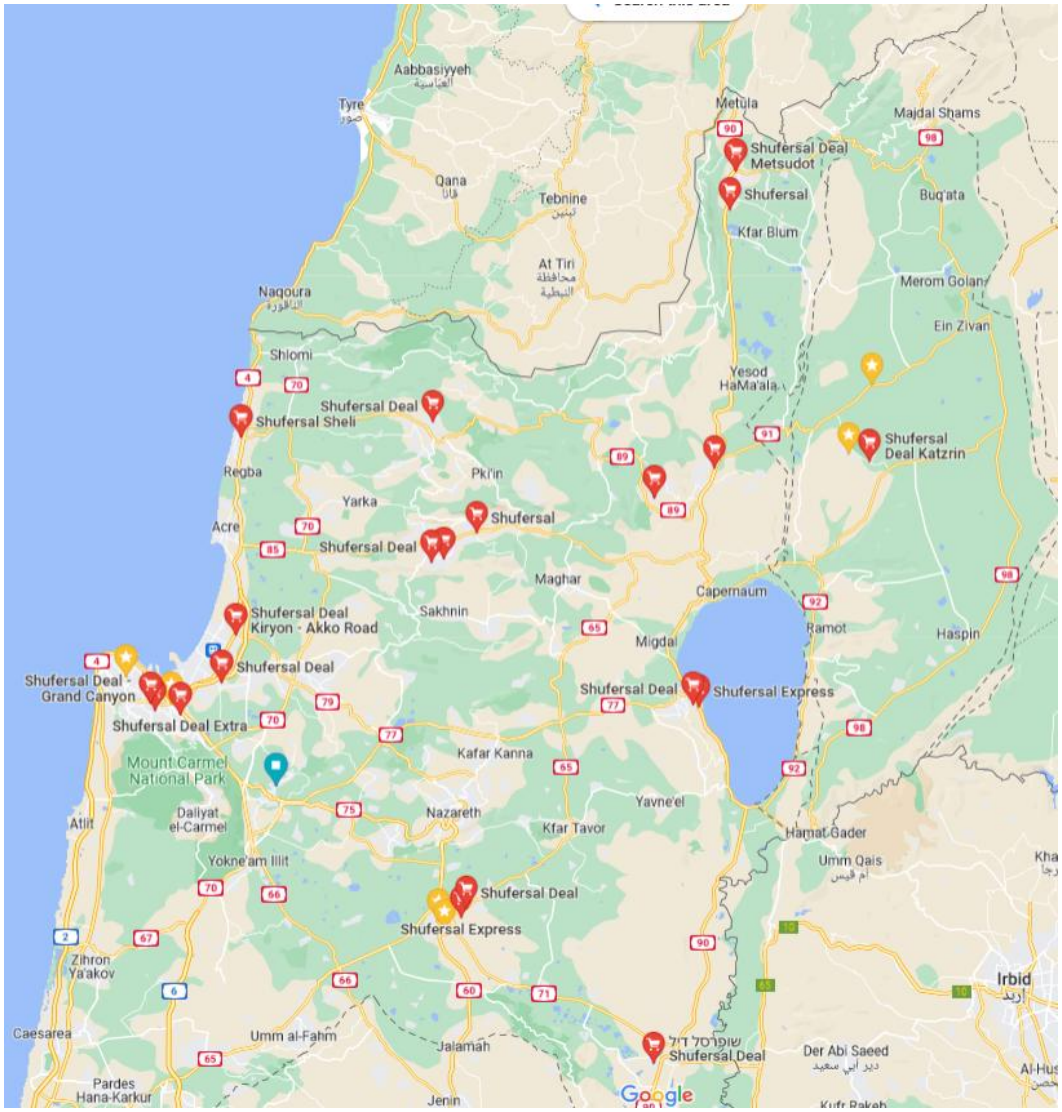


Replica Placement

Essence: Figure out what the best K places are out of N possible locations.

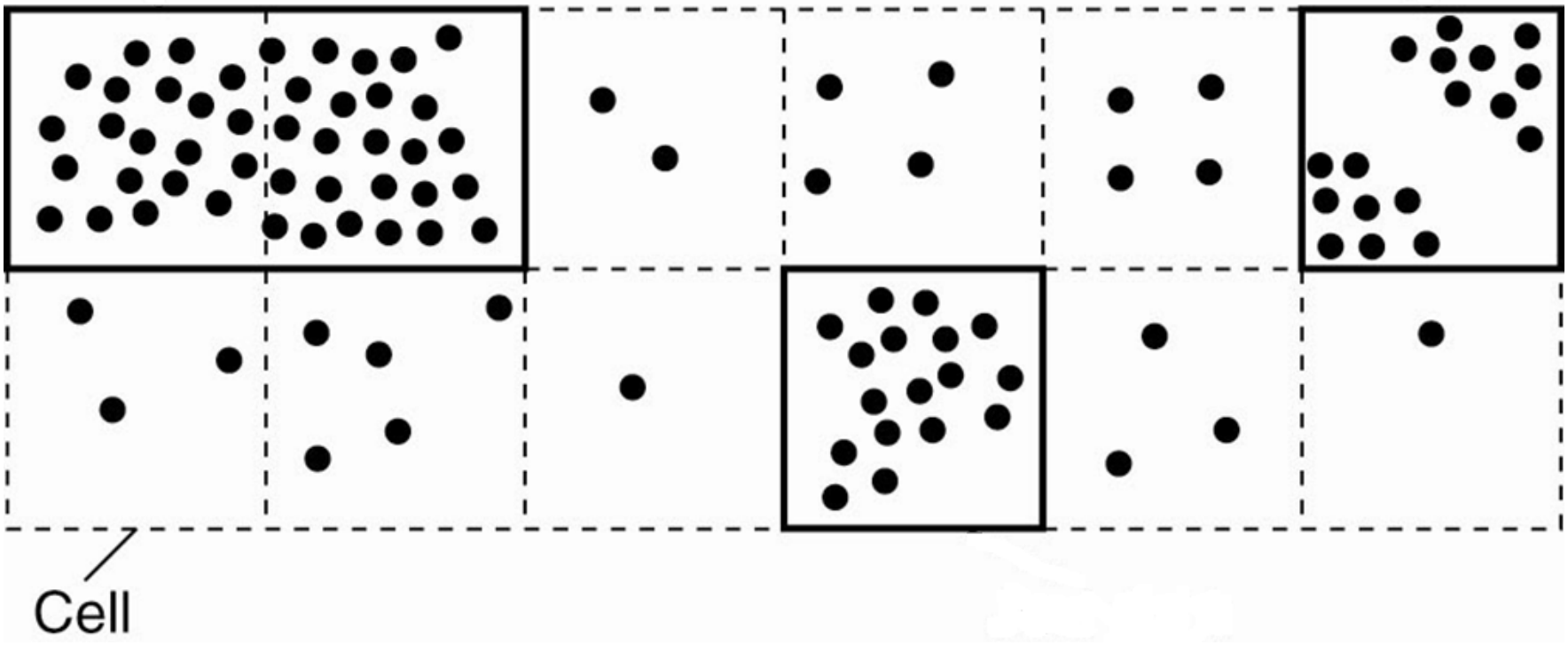
1. Select best location out of N for which the average distance to clients is minimal. Remove the location from N, add it to set k. Then choose the next best server until k has K elements. (Note: The first chosen location minimizes the average distance to all clients.) Computationally expensive (imagine 50 out of 1K locations, 5M clients).
2. Select the K^{th} largest autonomous system and place a server at the best-connected host. Computationally expensive (where is the best connected host?)
3. Position nodes in a d-dimensional geometric space, where distance reflects latency. Identify the K regions with highest density and place a server in each. Computationally cheaper.

Going to add one more Shufersal.



Where should we put it?

Densest Cells



I chose where to put the servers. What content do they store?

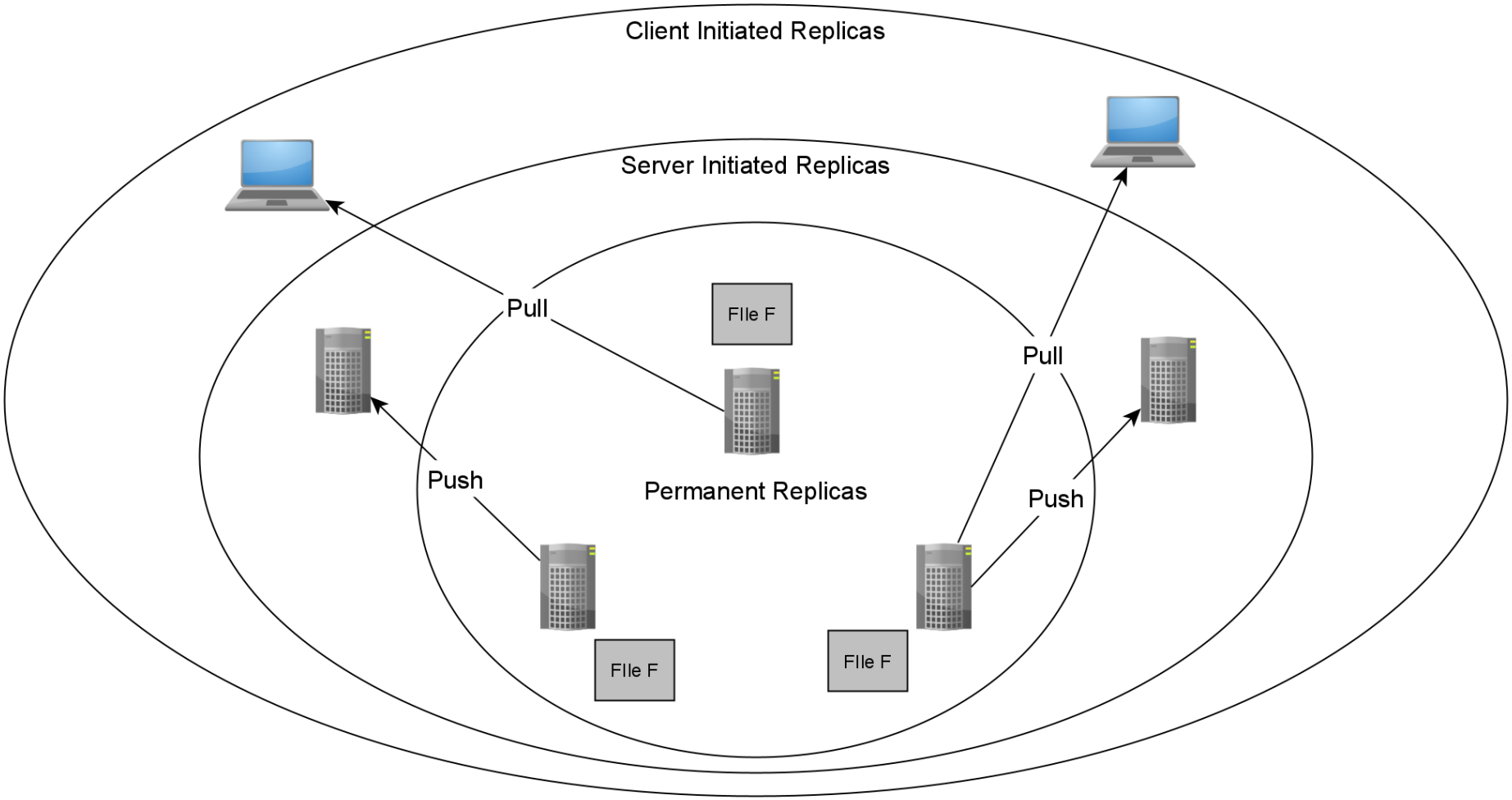
Content Replication

Model: We consider objects (and don't worry whether they contain just data or code, or both)

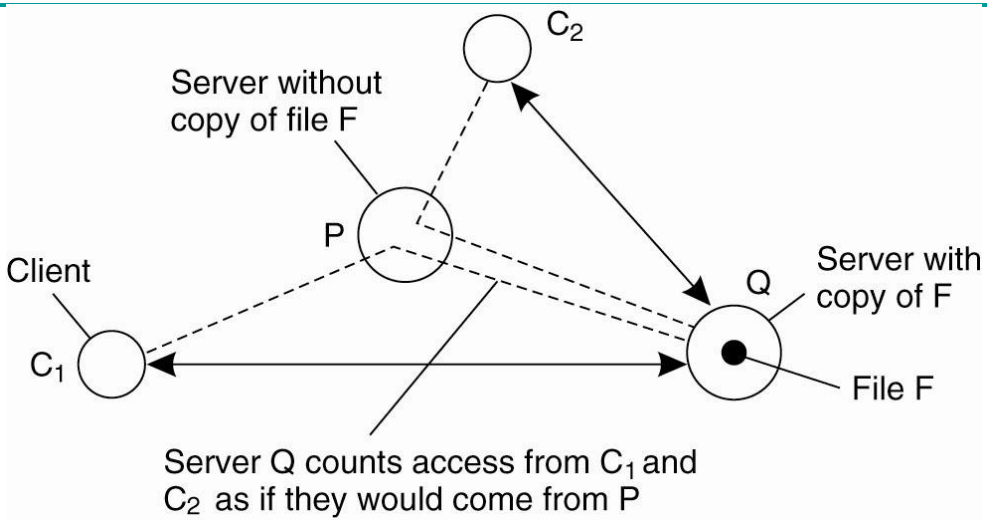
Distinguish different processes: A process is capable of hosting a replica of an object or data:

- **Permanent replicas:** Process/machine always having a replica
- **Server-initiated replica:** Process that can dynamically host a replica on request of another server in the data store
- **Client-initiated replica:** Process that can dynamically host a replica on request of a client (client cache)

Content Replication Types



Server-Initiated Replicas



Keep track of access counts per file, aggregated by considering server closest to requesting clients

When evaluating a file's storage:

- If the number of accesses drops below threshold D ⇨ drop file
- If the number of accesses exceeds threshold R ⇨ replicate file
- Between D and R → You may try to migrate it
  - To the replica which would have gotten more than half of the requests
  - The farthest replica with more than c percent of the requests

How do I move content around?

Model: Consider only a client-server combination:

Propagate only notification/invalidation of update (often used for caches)	Transfer data from one copy to another (distributed databases)	Propagate the update operation to other copies (also called active replication)

Observation: No single approach is the best, but depends highly on available bandwidth and read-to-write ratio at replicas.

Content Distribution

- Pushing updates: server-initiated approach, in which update is propagated regardless whether target asked for it.
- Pulling updates: client-initiated approach, in which client requests to be updated.

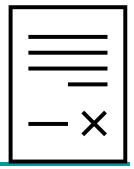
Issue	Push-based	Pull-based
1:	List of client caches	None
2:	Update (and possibly fetch update)	Poll and update
3:	Immediate (or fetch-update time)	Fetch-update time

1: State at server

2: Messages to be exchanged

3: Response time at the client

Leasing



Observation: We can dynamically switch between pulling and pushing using leases: A contract in which the server promises to push updates to the client until the lease expires.

Tweak: Make lease expiration time dependent on system's behavior (adaptive leases):

- **Age-based leases**: An object that hasn't changed for a long time, will not change in the near future, so provide a long-lasting lease
- **Renewal-frequency based leases**: The more often a client requests a specific object, the longer the expiration time for that client (for that object) will be
- **State-based leases**: The more loaded a server is, the shorter the expiration times become

Conclusion

- Data Oriented Consistency
- Client centric consistency
- Consistency Protocols
- Replica management
  - Content Replication
  - Content Distribution